Monitoring Corn and Soybean Crop Development with Hand-Held Radiometer Spectral Data

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Red and photographic infrared data were collected with a hand-held radiometer under a variety of conditions at 4- to 12-day intervals throughout the growing season and were used to monitor corn and soybean growth and development. The normalized difference transformation was used to effectively compensate for the variation in irradiational conditions. With these data, plotted against time, green-leaf biomass dynamics were compared between the crops. By this approach, based entirely upon spectral inputs, the crop canopies were nondestructively monitored. Five spectral stages were defined and were related to crop development for corn and soybeans.

Introduction and Review

Remotely sensed spectral radiance and reflectance data have been used in an attempt to temporally monitor vegetative conditions for several types of plant cover. Rouse et al. (1974) used LANDSAT MSS data from the American Great Plains to assess the green-wave effect from that area. They found that a simple ratio of MSS7/MSS5 (MSS7 = 0.80–1.10 μm and MSS5 = 0.60–0.70 μm) could be used as a measurement of relative greenness, but location, cycle, and atmospheric deviations would introduce a large error component. The difference of the MSS7-MSS5 radiance values was normalized over the sum of MSS7 and MSS5 and used as a value called the "vegetation index" (VI) in order to minimize this error component.

Carneggie et al. (1974) plotted a MSS7/MSS5 ratio as a function of time and found that the curves peaked during the period of greatest forage production. Thereafter, the curves fell off and reflected the period of drying for their California study sites.

Blair and Baumgardner (1977) used LANDSAT imagery to monitor several hardwood forest sites. They used the VI, which they call the "band ratio parameter," and found that the green-wave effect could be monitored for forests by use of LANDSAT imagery.

Ashley and Rea (1975) reported that LANDSAT MSS5 and MSS7 data were used to depict phenological change. They

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also found that the VI increased with foliage development and decreased with senescence. The VI reduced multiplicative effects such as solar elevation differences between overpasses (Ashley and Rea, 1975).

In most seasonal remote sensing studies, LANDSAT data were used because of the 18-day repeat cycle. Kanemasu (1974), however, reports on one of the few published ground-based reflectance studies of crops. He used a spectrometer to monitor wheat, sorghum, and soybean plots periodically during the growing season. He concluded that the 0.545/0.655 μm wavebands provided useful information regardless of crop type. For all crops studied, the ratio closely followed crop growth and development, and appeared to be more desirable than the near-infrared reflectance as an index of growth.

Tucker (1979) studied *in situ* reflectance of grass for a period of high and predominately (80%) green biomass (June), a period of high biomass with 50% green and 50% standing dead biomass (early September), and a period of completely dead standing biomass (mid-October). The various linear combinations of the red and photographic IR wavelength intervals were highly related to the green-leaf biomass.

In most of the seasonal remote sensing studies, red and photographic IR data were used. Most workers found that the green/red ratio reported by Kanemasu was less useful than the IR/red ratio or a related transformation such as the VI.

The red reflectance is less of green crops over a soil background than of exposed soil of the same type because of chlorophyll absorption. However, the IR reflectance ($\sim$0.74–1.00 μm) is greater for green crops than for the exposed soil surface because reflectance is enhanced in the absence of absorption. A ratio of these two reflectance variables or an associated transformation, such as the VI, has been reported to compensate for differences in the soil background spectra (Colwell, 1974) and contains information about the chlorophyll–green-leaf biomass interaction. The green reflectance ($\sim$ 0.50–0.60 μm), by comparison, does not have the same green-vegetation–soil-reflectance contrast as the red or photographic IR reflectances (Fig. 1). This difference results from the fact that the chlorophylls are slightly absorptive (pigment extinction coefficients = $\sim$7) in the green region and have no measurable absorption in the $\sim$0.74–1.00 μm region. The red region, by contrast, has chlorophyll extinction coefficients ranging from $\sim$40 to 90 (Salisbury and Ross, 1969). The extinction coefficients that we used are equal to the absorbance (optical density) given by a solution of the absorbing species at a concentration of 1 g/liter with a thickness (light path length) of 1 cm.

Spectral information about the chlorophyll concentration is thus more strongly evident in the red than in the green regions of the spectrum. Because the chlorophyll extinction coefficients are an order of magnitude greater in the red region than in the green region, a much greater soil–green-vegetation spectral reflectance and radiance contrast exists in the red region (Fig. 1). For these reasons, most LANDSAT investigators, who have done the most remote sensing of vegetation research, have used the red (MSS5) and IR (MSS6 or MSS7) bands in their analyses. The LANDSAT green band (MSS4) has not been nearly as widely

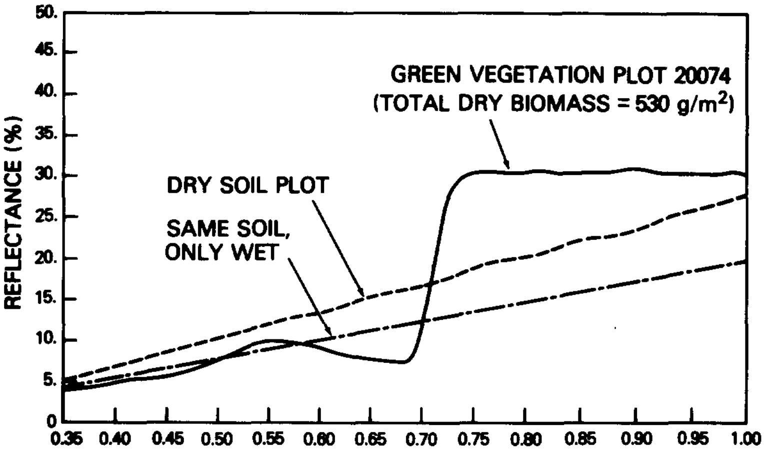


FIGURE 1. Spectral reflectances for dry soil, wet soil, and the asymptotic green reflectance. The dry soil and wet soil are for the same soil type, where five exposed soil plots of each were measured dry and wet, respectively. The asymptotic green reflectance curve is from a plot of blue grama grass having a total dry biomass of 530 g/m^2 (from Tucker and Miller, 1977).

used for vegetation as MSS5, MSS6, or MSS7 (Rouse et al., 1974; Carneggie et al., 1974; Ashley and Rea, 1975; Blair and Baumgardner, 1977; among others).

Red and photographic IR spectral measurements are ideally suited for monitoring the green-leaf area or biomass (reviewed in Tucker, 1979). If some straightforward means of normalizing for different irradiational conditions could be used, red and photographic IR irradiance data might be used to nondestructively monitor the green-leaf biomass of crops throughout the growing season.

Most remote sensing research efforts to date have used either LANDSAT data (NASA, 1973a; NASA, 1973b; Williams and Carter, 1976; Short et al., 1976; among others) or, to a lesser extent, laboratory data from spectra of leaves (Gausman et al., 1976; Olson, 1967; among others), or ground-based *in situ* spectrometric data (Kanemasu, 1974; Miller et al., 1976; among others). *In situ* data are invaluable for research purposes and as a means of better understanding satellite imagery of the earth's surface. Unfortunately, ground-based *in situ* spectrometric studies have often suffered because these instruments usually are cumbersome and lack mobility and spatial coverage. These instruments, however, give detailed spectral measurements.

A new approach has been developed for overcoming the limitations of the ground-based *in situ* spectrometric studies. This involves the use of hand-held spectral radiometers as first reported by Pearson and Miller (1972). This new approach results from and is closely associated with detailed *in situ* spectrometric studies (Tucker, 1978), where detailed spectrometric data are used to determine the wavelength regions of interest. Then, a simple, hand-held radiometer can be used with custom-made interference filters configured exactly for the wavelengths determined to be most interesting in the detailed spectrometric analysis.

Subsequently, hand-held radiometers can be used to adequately cover the spatial variability present in the research task at hand. They are light, sturdy, and portable. Because of these factors, they can be used to collect basic data about vegetated surfaces in a controlled experimental setting. Such data could increase the knowledge about remote sensing of vegetation and serve as the basis for improved use of remotely sensed information. The *in situ* data should also discourage or prevent overly ambitious applications of remote sensing when no causative relationship exists for the particular task at hand.

The use of remotely sensed multispectral imagery for monitoring the condition of agricultural crops and predicting yields has advanced rapidly. By necessity, much of this effort is coupled with ground-based data on crop development and climatic conditions throughout the growing season. Several numerical schemes for recording stages of crop development were developed (Hanway, 1963; Hanway and Thompson, 1971). One of the problems, however, in trying to monitor crop condition and predict yields has been the inability to collect on-the-ground developmental data over the large areas generally surveyed in remote sensing projects. Put simply, it is not feasible to collect developmental data on crops to supplement satellite imagery for any large-scale agricultural monitoring project. In foreign locations, access may be impossible and, in locations such as North America or Australia, labor costs might be excessive. A possible solution would be to generate a crop development value whose inputs would come entirely from remote sensing sources.

We now describe such a method, in which remotely sensed data were collected by a two-channel hand-held radiometer. We wanted to determine whether spectral data collected on the ground could be used to make qualitative and/or quantitative inferences about the stage of growth of corn and soybean crops. Basic to this objective was the evaluation of simple radiance transformations that were used to avoid the need for sun-angle corrections, atmospheric adjustments, and solar irradiance compensations.

Experimental Methods

A field of Elinsboro sandy loam soil located on the USDA Beltsville Agricultural Research Center was selected for this study. Four 6-m $\times$ 6-m plots each of corn and soybeans were planted on April 28 (Julian date 118) and May 20 (Julian date 140), 1977, respectively. Row spacing was 91 cm (23 cm within the row) for the corn, and 76 cm (5 cm within the row) for the soybeans. Agronomic data pertaining to crop development, percentage crop cover, and plant height were recorded weekly throughout the growing season. Crop development was recorded by use of numerical scales devised for corn (Hanway, 1963) and for soybeans (Hanway and Thompson, 1971). Percentage crop cover and percentage chlorosis (leaf yellowing) were visually estimated for each plot, and plant height was measured in centimeters. A large field ($\sim$1 ha) of each crop also was planted at about the same time. Four 6-m $\times$ 6-m areas were designated in each field and monitored as a check on the validity of data from the small plots.

Each week, using a two-channel hand-held digital radiometer slightly modified from that described by Pearson et al. (1976), 16 red and 16 photographic IR radiance measurements were made for each soybean plot; 24 were made for each corn plot. The radiometer was modified from that used by Pearson et al. by the removal of the digital interface and hand-held calculator. Data were collected from a 1.5 − m ladder for corn plots and from the ground for the soybean plots. The radiometer was held ~3.5 m and ~2.0 m above the ground surface for the corn and soybean canopies, respectively. Data from each experimental plot were averaged and the mean values were used in the analysis. Immediately prior to each series of spectral measurements on a given plot, a solar intensity calibration reading was taken from a $BaSO_4$ panel. All measurements were corrected normal to the canopy surface between 1100 and 1500 hr under sunny conditions.

Although we had wanted to sample the experimental plots every 7 days, overcast conditions often precluded the 7-day sampling procedure. Actual measurements were usually made at 6- to 8-day intervals; the minimum interval was 4 and the maximum, 12 days. Data were collected in direct sunlight under cloudless or partly cloudy skies. Haze conditions varied from very clear with low humidity, to hazy with high humidity.

Several radiance normalization techniques were applied to the data. The individual red and photographic infrared readings were transformed into the IR/red ratio, the IR-red difference, the IR + red sum, the vegetation index (VI) of (IR−red)/(IR + red), and transformed vegetation index (TVI) of $\sqrt{VI + 0.5}$ (the VI and TVI are after Rouse et al., 1974). Each of the spectral variables was evaluated for the radiance data and the reflectance data. Reflectance was determined by dividing the plot radiance measurements by the $BaSO_4$ reference measurements. However, in satellite and aircraft analyses, generally only radiance data are used. Analysis of satellite and aircraft data in reflectance units may be impractical because of the need for many reference readings. Therefore, results for the radiance variable only are presented here because they represent the uncalibrated data that resemble that collected from aircraft and/or satellite platforms.

The same types of remotely sensed data can be collected by the LANDSAT-1, -2, and -3 multispectral scanner (MSS) system bands MSS5 and MSS6 or MSS7. LANDSAT-D, scheduled for launch in 1981, will provide from its thematic mapper (TM) scanner system data that are much superior to those from LANDSAT-1, -2, and -3. Thematic mapper bands TM 3 (0.63–0.69 μm) and TM 4 (0.76–0.90 μm) should provide excellent satellite data for objectives that are the same as those used in this experiment.

Results and Discussion

Normalization of radiance data

The red and photographic IR radiance values showed the effect of changing amounts of green-leaf biomass over the soil surface with increasing Julian date in both corn and soybean plots (Fig. 2). The red radiance decreased rapidly with time,

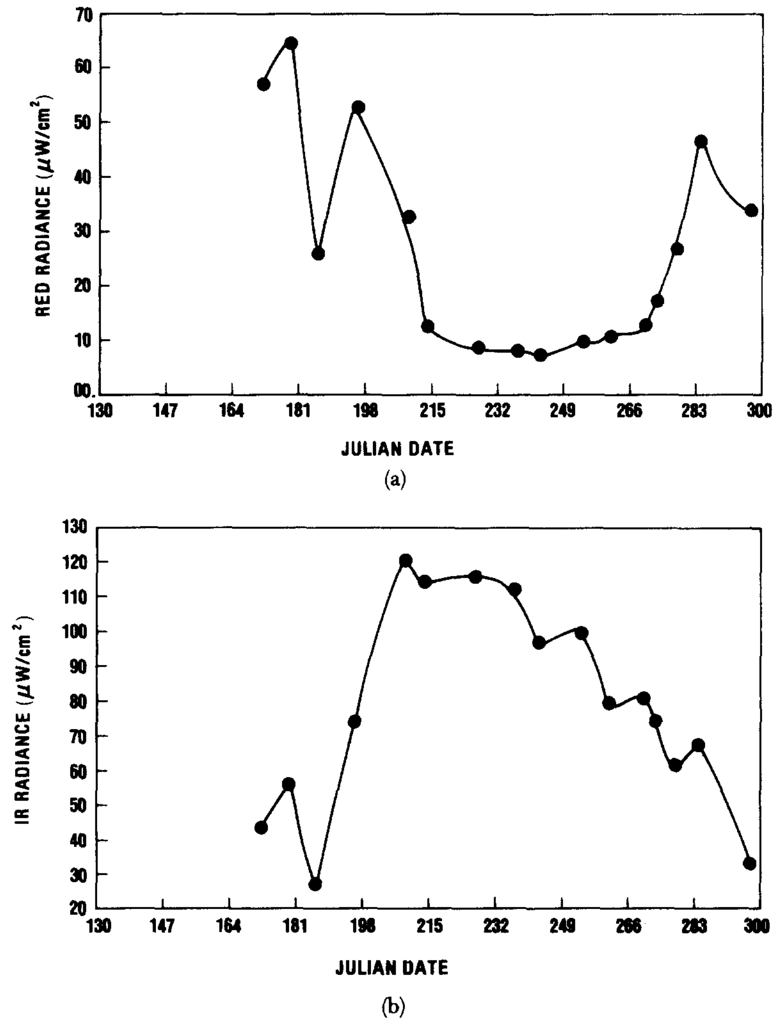


FIGURE 2. Red and photographic IR radiances plotted against Julian date for a typical experimental soybean plot: (a) red radiance and (b) IR radiance. The radiance data are not normalized. The red radiance was collected from the 0.65–0.70 μm region while the IR radiance was collected from the 0.775–0.825 μm region.

because of increased chlorophyll absorption by increased green-leaf biomass, until the growing season waned and senescence began [Fig. 2a]. At that time, the red radiance began to increase as the chlorophyll level in the plant canopy declined through chlorophyll breakdown and/or leaf loss. The red radiance asymptote was reached early in the growing season. This can be interpreted in two ways: (a) The red radiance asymptote was reached because additional green-leaf biomass that was low in the canopy would not receive any incident red light (i.e., the red light was extincted via chlorophyll absorption) or (b) the various abiotic and biotic variables, other than light penetration, that control plant growth and development became limiting. The data in Fig. 2(a) represent the red light extinction situation.

The photographic IR radiance increased with time and with green-leaf biomass [Fig. 2(b)]. This increase was gradual and peaked only to gradually fall off as the growing season continued. The photographic IR radiance asymptote was reached at levels of green-leaf biomass that are two to three times as great as that for the red radiance or reflectance (Gausman et al., 1976; Tucker, 1977).

As can also be seen in Fig. 2, the radiance data (particularly the IR data) were scattered erratically by varying solar intensities, sun angles, and atmospheric conditions at the different data collecting times. The five radiance normalization techniques (transformations) applied effectively compensated for this variability. However, the most useful transformations were the IR/red ratio, the VI, and the TVI shown in Fig. 3, with preference for the VI.

Spectral stage of growth

Agronomic and spectral measurements were similar for the corn and soybean plots [Fig. 4(a) and 4(b)]. Significant linear correlation coefficients indicated that percentages of crop cover and chlorosis were closely associated with the VI. As crop cover increased or decreased, a corresponding change was measured by the VI, $r=0.51$ ($n=38$) and $r=0.80$ ($n=38$) for the corn and soybeans, respectively. An increase in plant chlorosis resulted in a decrease in the VI, $r=-0.99$ ($n=18$) and $r=-0.94$ ($n=18$). Plant height, a function of the early season accumulation of crop cover, also appeared closely associated with the VI during the early season when crop development was rapid. However, by late season, with the onset of chlorosis due to crop maturation, it became obvious that the VI was mostly responsive to fluctuations in green vegetative crop cover associated with the sequence of crop development and maturation. Data were similar for the large fields and the small plots.

Five phenological stages of spectral crop development (SCD) were observed for corn and soybeans [Fig. 5(a) and 5(b)].

Stage 1. For both crops, the VI for the bare soil before crop emergence and after emergence up to 20–30% cover was negative.

Stage 2. The rapid increase in vegetative crop cover for both corn and soybeans prior to bloom was indicated by a rapid increase in VI.

Stage 3. Once vegetative crop cover was complete, VI reached a plateau. Stage 3 of SCD continued during bloom and until chlorosis was detected.

Stage 4. During Stage 4, the period of crop maturation and dry-down, VI declined gradually. Leaves became chlorotic and were often lost from the plants.

Stage 5. At SCD Stage 5, the soybeans had lost all leaves and the corn had lost all color, i.e., the crops were ripe and ready for harvest. The VI resembled that measured at crop emergence.

The two principal factors that influence or control the VI measurements of crops are the chlorophyll density and green-leaf biomass per unit area. Conditions that affect either chlorophyll density or green leaf biomass are expressed in the VI values. For example, stress conditions, such as drought, would affect the VI by limiting plant growth such that the plateau would be reached at a later date, or a lower level would be attained. Or, if drought conditions occurred after the

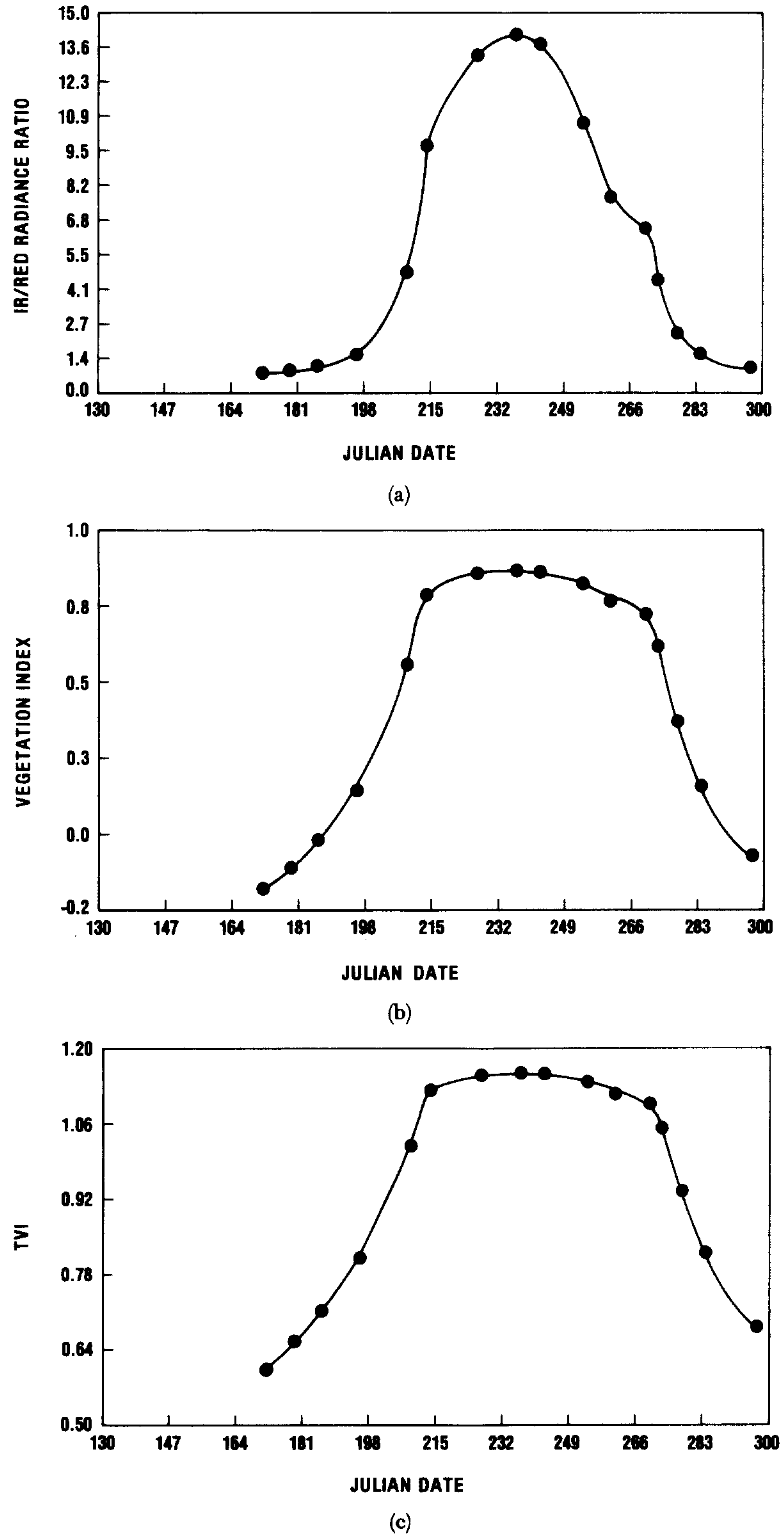
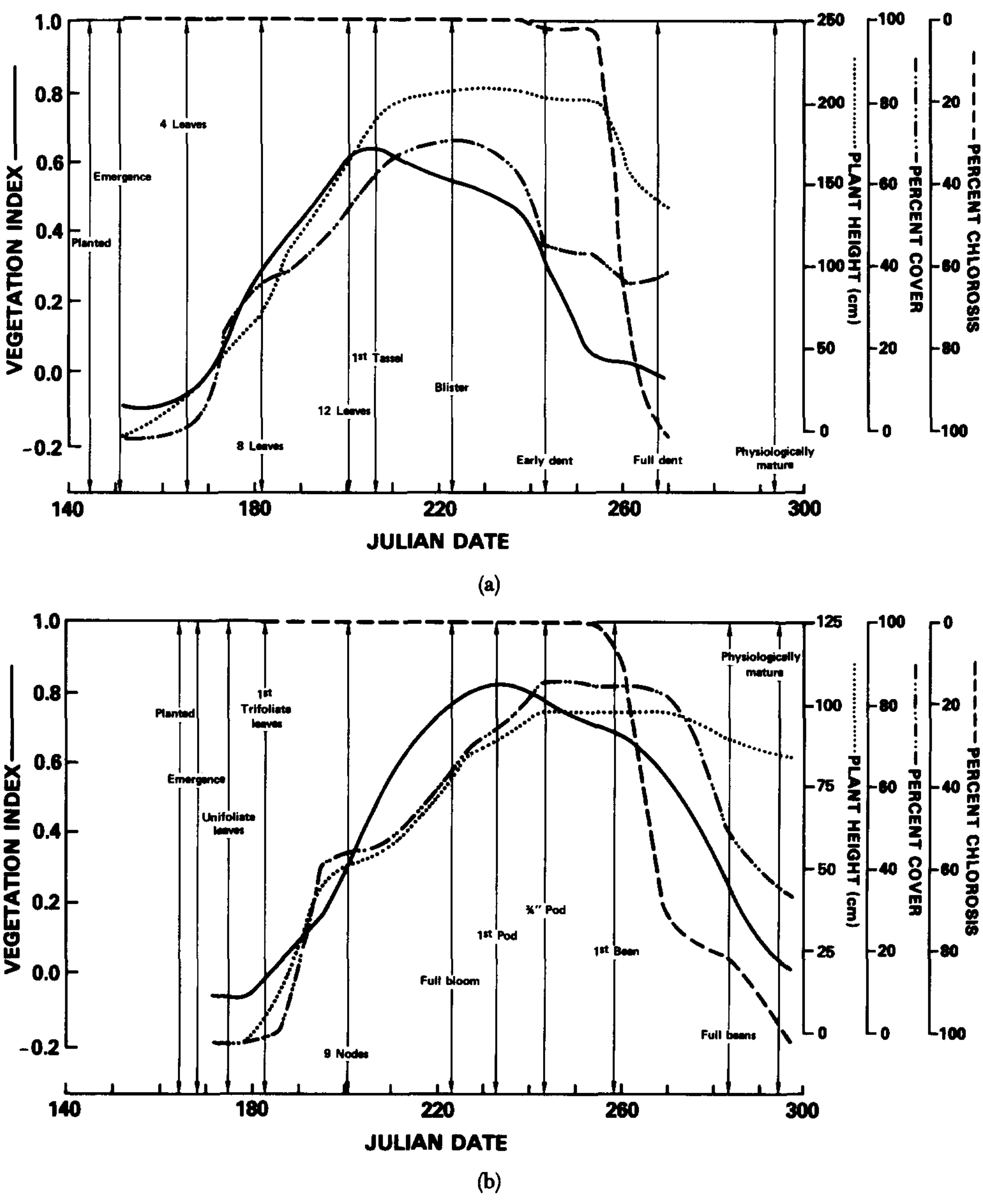


FIGURE 3. The (a) IR/red radiance ratio, (b) Vegetation index (VI), and (c) Transformed vegetation index (TVI) plotted against Julian date for a typical experimental soybean plot. Refer to Fig. 2(a) and 2(b) for the radiance data used in this figure. Note how these transformations effectively compensate for variations in solar intensity.



(a)

(b)

FIGURE 4. The vegetation index (VI), plant height, estimated crop cover, and estimated chlorosis are plotted against Julian date for (a) corn and (b) soybeans. Agronomic data pertaining to stage of growth are also noted with respect to Julian date. Each plot is the average of two replicates having the same agronomic treatment.

plateau had been reached, the plant canopy would respond by wilting and the VI would decline.

Chlorosis, a decrease in chlorophyll density that is brought about by unfavorable environmental factors, would also depress VI values. Soil fertility, particularly nitrogen, would affect the accumulation and density of green biomass and thus would be expressed in the VI. High fertility would elevate and low fertility would depress the VI values.

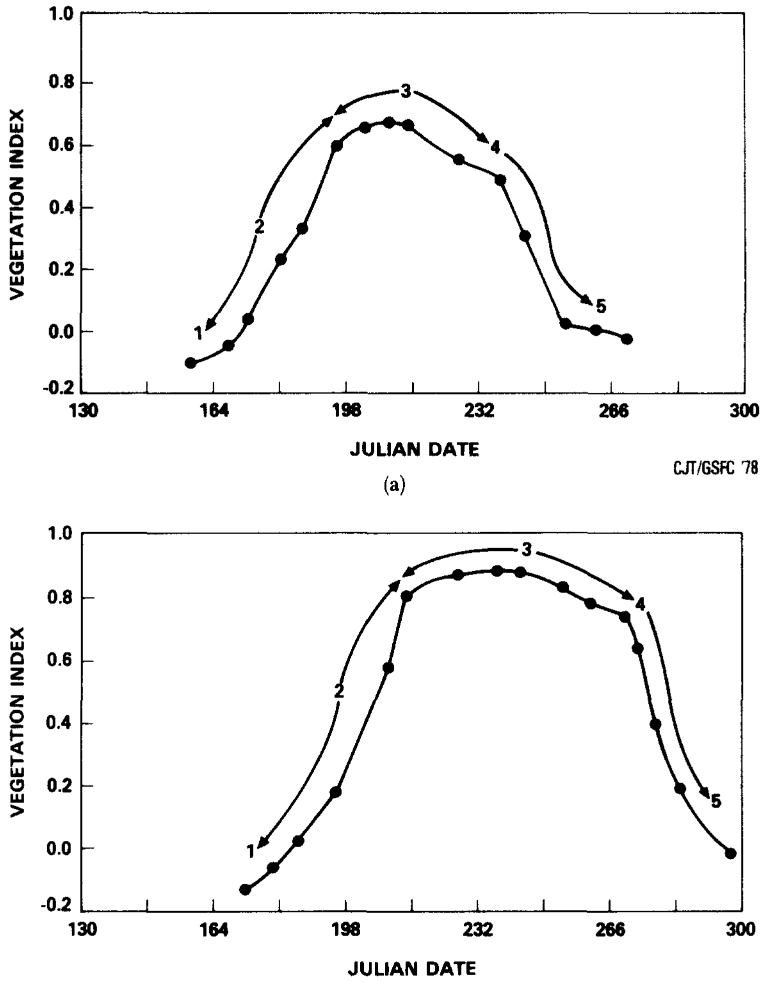


FIGURE 5. Spectral crop development stages for (a) corn and (b) soybeans. Five stages are apparent: 1. Emergence up to 20–30% vegetation cover; 2. Rapid foliar growth and development; 3. Full vegetative cover; 4. Onset of senescence, maturation of crop, and dry down; 5. Crop maturity, ready for harvest. Average vegetation index (VI) is plotted against Julian date for two replicates for each crop.

Unfortunately, weeds pose a confounding problem for the VI, which is sensitive to green biomass whether weeds, crop, or weeds and crop. However, the sensitivity to weeds by the VI might be exploited to detect the presence of substantial patches of weeds. Unexpectedly high values for the VI early in the growing period could indicate the presence of some foreign type(s) of green-leaf biomass (Fig. 6).

The relationship between the VI and crop development that we observed indicated the crop condition could be assessed through spectral measurements. Attaining and sustaining full vegetative cover stage is an important factor in the final yield of any crop. The spectral assessment of the stages of crop development could be important in the prediction of yield by remote sensing.

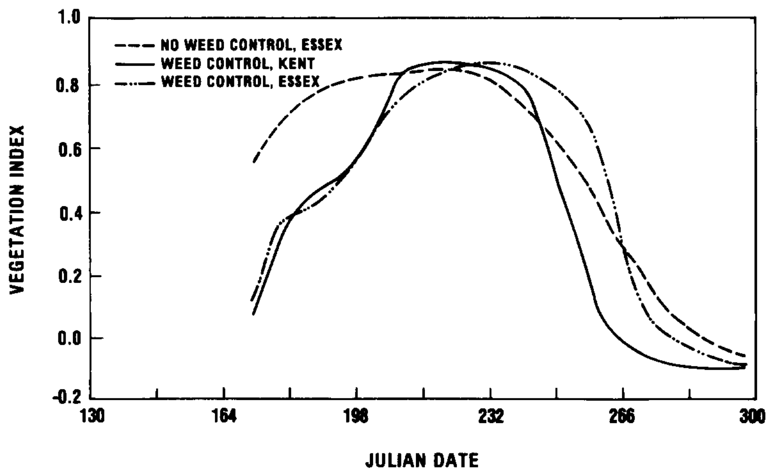


FIGURE 6. Comparison between the Vegetation indices for three agronomic treatments for soybeans. Note how the presence of weeds in the "no weed control" plot resulted in higher VI values than the other soybean treatments with weed control earlier in the growing season.

Summary

Hand-held radiometer data were used to nondestructively monitor corn and soybean crop canopies throughout the growing season.

Linear combinations of the red and photographic IR radiance data were used to normalize data for the different irradiational conditions present during the study period.

A system for monitoring the stages of crop development based solely upon red and photographic IR spectral measurements was proposed for corn and soybeans.

Five distinct and spectrally measurable stages were defined for corn and soybeans:

1. Emergence up to 20-30% vegetative cover
2. Rapid foliar growth and development
3. Full vegetative cover
4. Onset of senescence, crop maturation, and dry-down
5. Crop maturity, ready for harvest.

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